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Analytical determination of wear resistance criteria of a stamping tool for various loading conditions

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Introduction. The paper is devoted to the analytical determination of general criteria for predicting the wear resistance of heavily loaded friction couples, in particular, stamping tools, operating under various loading conditions. The proposed system of criteria is based on physical dependencies that link the basic wear index, i.e. the number of loading cycles N_F with crack resistance parameters n and C. The work objectives were the development and analytical foundation of the calculation technique that provides for predicting the wear resistance of the stamping tool for various loading conditions, as well as the predetermination of experimental verification of the efficiency of the developed methodology.
Materials and Methods. Mathematical models that link the key criterion of wear-resistance, the number of loading cycles N_F with crack resistance parameters n and C, are proposed. An analytical verification of the proposed models is carried out.
Results. Mathematical models are developed for predicting the wear resistance of a stamping tool operating under various loading conditions. In particular, for the following cases: under sliding and rolling friction of the tool on a plastically deformable metal, for conditions of thermo-mechanical contact fatigue, for high-cycle brittle contact damaging, for pulsating contact on a plastically deformable metal, as well as for combined types of frictional contact.
Discussion and Conclusions. The results obtained can be used in the design and structural optimization of the stamping tool operating under various loading conditions, as well as in predicting its life cycle.

Keywords: stamping tool, wear resistance criteria, loading conditions, contact damaging, crack resistance, sliding, rolling, surfacing materials.

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Introduction. Experimental and theoretical studies on the wear processes of surfacing materials show that no material properties separately can determine the wear resistance under the frictional contact extreme conditions in a unique manner. Only a certain set of physical and mechanical properties with account of the frictional interaction features should be considered when determining the wear resistance of surfacing materials.

Wear resistance criteria should meet the conditions of specific tribocouplings. To determine the criteria, a single approach should be followed in each case. Obviously, for all the phenomena and types of contact damage, the principle condition should be taken into account: that material is considered more wear-resistant whose stage of fatigue crack growth is longer. Thus, the wear resistance criterion should take into account the duration of the process of destruction of the surface layer and separation of the first wear particle. In this case, the determination of the wear resistance criterion is reduced to evaluation of the cycle index N_F at which the surface layer destruction occurs.

In this case, the assignment of wear resistance criteria may consist not in calculating the contact endurance of materials, but in comparing and selecting surfacing materials for specific frictional contact conditions that are characteristic of heavy loaded friction couples. Thus, the criteria should provide adequacy of the wear resistance series for specific types of friction contacts.

In accordance with a unified approach, the following key points should be taken into account when determining the criteria. One type of crack should be considered in all types of frictional contact. Generically, the crack resistance parameters of materials that determine the kinetics of the development of fatigue microcracks should be taken into account. When comparing surfacing materials with each other according to the criteria, it is required to consider the possibility of developing a competing type of wear — low-cycle viscous damage as a result of the petal peeling.

Materials and Methods. For reversible sliding conditions on a plastically deformable metal, the author first proposed a method for analyzing wear resistance considering the basic properties of the material, which determine the surface layer destruction under friction [1].

It appears possible to determine the wear resistance criterion with account to the fracture toughness, yield strength, friction coefficient, and initial crack sizes. The studies [2–9, 11, 13, 15, 16] show that this approach is also promising for other frictional contact conditions characteristic of heavy loaded friction couples including a stamping tool.

V.V. Rubanov, assuming that the criterion proposed for reverse sliding in [1], and using the dependence of the yield strength on a number of characteristics of the structure of the material, proposed to determine the wear resistance of the material according to the criterion [4]:

$$K_и = \frac{\left(\sigma_м l_i + 11Gb\dfrac{\phi}{1-\phi}\right)\cdot K_{1c}}{f^2 l_i^{3/2}}, \tag{1}$$

where $\sigma_м$ is the ultimate mechanical stress in the material from the action of the matrix under which its destruction occurs; l_i is the average defect size; K_{1c} is fracture toughness; φ is the volume fraction of defects; G is the shear modulus; b is Burgers vector; f is the friction factor (from now on, the friction factor is applied on the ground of the Siebel law).

Given that for a number of alloys, there is the dependence K_{1c} on the tensile strength under bending $\sigma_{изг}$, after a series of simplifications, V.V. Rubanov recommends the following criterion for assessing the wear resistance of surfacing materials:

$$K_и = \frac{G\cdot\phi\cdot\sigma_{изг}}{f^2\cdot(1-\phi)\cdot l_i^{3/2}}. \tag{2}$$

This approach has limited possibilities due to the following. The proposed criterion is common for various frictional contact schemes; and when determining the wear resistance of surfacing materials for sliding and rolling according to the criterion (2), differences in the contact damage mechanism are not taken into account under the conditions of contact interaction for sliding and rolling, both with tangential with effort or without it.

The wear resistance criterion (2) does not take into account the crack resistance parameters of materials that affect directly the rate of development of fatigue microcracks, and, therefore, determine the duration of contact damage processes.

Research Results. In the analytical definition of wear resistance criteria, the basic assumption should be made: the field of contact tensile stresses is uniform, and its value is equal to the maximum value that is determined on the surface. Thus, this assumption does not take into account the gradual attenuation of tensile stresses in the depth of the material and is a more stringent estimate. The studies [10] show that the errors arising in this case are small if the length of the cracks is less than the depth of the zone of compressive stresses.

The task of determining the criteria for the wear resistance of materials wearing under the contact damage conditions is as follows. It is required to analytically determine the time (the number of contact interaction cycles) of separating the particles of abnormal wear. In this regard, the stresses that act on the crack in a particular frictional contact should be used as tensile stresses.

Given the differences between low-cycle brittle contact damage and multi-cycle damage, the problem of determining the criteria for wear resistance is divided into two types. In the first case, when determining the contact fracture process time for low-cycle brittle contact damage, it is required to consider the possibility of reaching a critical crack. In the second case for low-cycle brittle contact damage, it was found that cracks do not reach critical values ($l_c >> l_i$). Here, it is possible to use the maximum permissible size of spalling as the final crack length (it is established either from the requirements for wear tolerance of tribocoupling or from the requirements for limiting the size of contact damage on the edge of the working surface).

Wear resistance criterion for sliding on plastically deformable metal

The contact fracture process time is determined through integrating the Paris equation [17]. As a value of tensile stresses for this case of frictional contact, we should take [10]:

$$\sigma_{p\max} = \frac{4pf}{\pi}, \tag{3}$$

where p is the average pressure in contact.

In this case, the expression for the stress intensity factor takes the form:

$$\sigma_{p\max} = \frac{4pf}{\sqrt{\pi}}\sqrt{l} \,. \tag{4}$$

The fracture process time, and, consequently, the wear resistance criterion N_F, is defined as

$$N_F = \int_{l_i}^{l_k} \frac{dl}{CK^n l^{n/2}} = \frac{\pi^{n/2}}{C\left(4pf\right)} \int_{l_i}^{l_k} \frac{dl}{l^{n/2}} \,. \tag{5}$$

At n≠ 2, the expression (5) solution takes the form

$$N_F = \frac{2\pi^{n/2}}{(n-2)C(4pf)^n}\left(\frac{1}{l_i^{\frac{n-2}{2}}} - \frac{1}{l_c^{\frac{n-2}{2}}}\right). \tag{6}$$

From the basic principles of fracture mechanics, it is known that the critical crack length is the value at which the crack starts a supercritical self-motion. This moment determines uniquely the fracture toughness of the material K_{1C}. In the case of contact loading by a uniform stress field under sliding, the value of the critical crack length can be determined from the expression [10]:

$$l_c = \frac{\pi}{16p^2 f^2} K_{1c}^{f^2} \,. \tag{7}$$

After the corresponding replacement and transformations, we obtain

$$N_F = \frac{2\pi^{n/2}}{(n-2)C(4pf)^n}\left[\frac{1}{l_i^{\frac{n-2}{2}}} - \left(\frac{4pf}{\pi^{1/2}K_{1C}^f}\right)^{n-2}\right]. \tag{8}$$

This expression can be used as a criterion of wear resistance when sliding against a plastically deformable metal under the conditions of high contact pressures, when low-cycle brittle contact damage is realized. In this case, as follows from the expression (7), the wear resistance of surfacing materials is determined by the contact pressure, friction coefficient, fracture toughness, size of structural defects and crack resistance parameters *n* and *C*.

Wear resistance criterion for thermomechanical contact fatigue

The effect of heating-cooling cycles, which is characteristic primarily for a pulsating contact with a heated plastically deformable metal, on the friction surface causes the origination of periodic thermomechanical stresses in the surface layer. The expression of V. I. Dukhovchenko [12] for determining this type of stress is known as follows:

$$\sigma = \frac{\alpha E \Delta T}{1-v} \,, \tag{9}$$

where α is the thermal coefficient of linear expansion; E is the elasticity modulus; ΔT is the temperature difference of the heating-cooling cycle; v is the Poisson's ratio.

In this case, with regard to the expression (9), the solution to the integral for the Paris equation at n≠ 2 is determined from the formula:

$$N_F = \frac{2(1-v)^n}{(n-2)C\pi^{n/2}(\alpha E\Delta T)^n}\left(\frac{1}{l_i^{\frac{n-2}{2}}} - \frac{1}{b^{\frac{n-2}{2}}}\right). \tag{10}$$

If the limiting value $b_{\max}$, which is assigned as the tolerance on the limiting size of the centre of spalling of the working surface edges, is taken as l_c, we obtain

$$N_F = \frac{2(1-v)^n}{(n-2)C\pi^{n/2}(\alpha E\Delta T)^n}\left(\frac{1}{l_i^{\frac{n-2}{2}}} - \frac{1}{b_{\max}^{\frac{n-2}{2}}}\right) \tag{11}$$

or

$$N_F = \frac{2(1-v)^n\left(b_{\max}^{\frac{n-2}{2}} - l_i^{\frac{n-2}{2}}\right)}{(n-2)C\pi^{n/2}(\alpha E\Delta T)^n\, l_i^{\frac{n-2}{2}}\, b_{\max}^{\frac{n-2}{2}}} \tag{12}$$

This expression can be used as a criterion for the wear resistance of surfacing materials under thermomechanical fatigue. Under these conditions, wear resistance of materials also depends on the crack resistance parameters *n* and *C*, is determined by the tolerance for unit spalling, the elasticity modulus, the Poisson's ratio, and is inversely proportional to the coefficient of thermal expansion, the magnitude of the temperature difference and the size of the initial defects.

Wear resistance criteria for multi-cycle brittle contact damage

We consider $l_1 = l_i$ and take into account that when rolling with a tangential force and an elastic pulsating contact, the angle of crack development does not depend on the material properties and is close to 45°. Then, the following expression is obtained to determine the fracture process time under rolling with a tangential force:

$$N_F = \frac{2}{(n-2)C}\left[\frac{7.35}{(1+11f)\sigma_{z\max}}\right]^n \left(\frac{1}{l_i^{\frac{n-2}{2}}} - \frac{1}{l_c^{\frac{n-2}{2}}}\right). \tag{13}$$

For rolling without tangential force

$$N_F = \frac{2}{(n-2)C}\left[\frac{4.62}{\sigma_{z\max}}\right]^n \left(\frac{1}{l_i^{\frac{n-2}{2}}} - \frac{1}{l_c^{\frac{n-2}{2}}}\right), \tag{14}$$

Upon the pulsating contact

$$N_F = \frac{2}{(n-2)C}\left[\frac{6.65}{\sigma_{z\max}}\right]^n \left(\frac{1}{l_i^{\frac{n-2}{2}}} - \frac{1}{l_c^{\frac{n-2}{2}}}\right). \tag{15}$$

Since, under conditions of multicycle brittle contact damage, the cracks do not reach a critical value during development, $l_c >> l_i$, the expressions (13) - (15) can be transformed as follows:

– for tangential force rolling

$$N_F = \frac{2\cdot 7.35^n}{(n-2)C(1+11f)^n \sigma_{z\max}^n l_i^{\frac{n-2}{2}}}. \tag{16}$$

– for rolling without tangential force

$$N_F = \frac{2\cdot 4.62^n}{(n-2)C\sigma_{z\max}^n l_i^{\frac{n-2}{2}}}, \tag{17}$$

– for pulsating contact

$$N_F = \frac{2\cdot 6.65^n}{(n-2)C\sigma_{z\max}^n l_i^{\frac{n-2}{2}}}, \tag{18}$$

The obtained criteria for wear resistance indicate that in this case, too, the critical impact is exerted by the parameters of crack resistance of materials n and C, the size of the defects; and, in addition, in the case of rolling with a tangential force, the friction coefficient should be taken into account.

Wear resistance criterion for rolling against plastically deformable metal

A feature of this frictional contact type is that the counterbody acquires intense plastic deformation. In this case, stresses in the contact zone cannot be estimated through the formulas for elastic contact, and the wear resistance criteria (16) - (18) are not applicable.

To solve this problem, we use the analogy for rolling against a plastically deformable metal and sliding under the same conditions. Then, the crack will be periodically affected by a plastically deformable rolling body. Considering that rolling under these conditions is accompanied by significant spalling, we use the expression (6) for the sliding contact. As the final crack length, the limit tolerance for unit spalling of the working surface edge should be used.

In this case, the number of cycles for the destruction of the surface layer can be determined through the expression:

$$N_F = \frac{2\pi^{n/2}}{(n-2)C(4pf)^n}\left(\frac{1}{l_i^{\frac{n-2}{2}}} - \frac{1}{b_{\max}^{\frac{n-2}{2}}}\right). \tag{19}$$

After transformations, the expression (19) can be rewritten as follows:

$$N_F = \frac{2\pi^{n/2}\left(b_{\max}^{\frac{n-2}{2}} - l_i^{\frac{n-2}{2}}\right)}{(n-2)C(4pf)^n l_i^{\frac{n-2}{2}} b_{\max}^{\frac{n-2}{2}}}. \tag{20}$$

Thus, the wear resistance of surfacing materials when rolling against a plastically deformable metal is determined through the crack resistance parameters *n* and *C*, contact pressure, friction coefficient, limit tolerance on the size of the spalling and the sizes of the initial defects.

Wear resistance criterion for pulsating contact on plastically deformable metal

The characteristic features of this type of friction contact are extremely high contact pressures (up to 4000 MPa), which is associated with the dynamic nature of the application of the contact load. In this case, making use of the expression (18) for an elastic pulsating contact is also impossible.

For the maximum tensile stresses acting on the crack, we take the value that, at a first approximation, can be determined using the condition $\sigma_{z\max} \approx p$ from the formula:

$$\sigma_{p\max} = \frac{1-2\nu}{3} p \tag{21}$$

where *p* is average contact pressure.

The fracture process time is determined through the integration of the Paris equation for the given conditions of contact loading:

$$N_F = \int_{l_i}^{l_c} \frac{dl}{CK^n l^{n/2}} = \frac{3^n}{C\pi^{n/2}(1-2\nu)^n p^n} \int_{l_i}^{l_c} \frac{dl}{l^{n/2}} = \frac{2\cdot 3^n}{(n-2)\pi^{n/2}C(1-2\nu)^n p^n}\left(\frac{1}{l_i^{\frac{n-2}{2}}} - \frac{1}{l_c^{\frac{n-2}{2}}}\right). \tag{22}$$

Let us present the value of the critical crack length l_c through K_{1c}^f:

$$l_c = \frac{K_{1c}^f}{\pi\left(\frac{1-2\nu}{3} p\right)^2} \tag{23}$$

and we get after the transformations:

$$N_F = \frac{2\cdot 3^n}{(n-2)\pi^{n/2}C(1-2\nu)^n p^n}\left[\frac{1}{l_i^{\frac{n-2}{2}}} - \left(\frac{\pi^{1/2}(1-2\nu)p}{3K_{1c}^f}\right)^{n-2}\right]. \tag{24}$$

The given expression is a criterion for the wear resistance of surfacing materials for pulsating contact against plastically deformable metal. Under these conditions, wear resistance is determined by fracture toughness, crack resistance parameters, Poisson's ratio, contact pressure and the size of the initial defects.

Wear resistance criteria for integrated friction contact modification

Under the conditions of sliding friction against a heated plastically deformable metal, the tool working surface is subjected to alternating stresses from friction forces and thermomechanical stresses. In this case, according to the hypothesis of a linear summation of stresses, the stress intensity factor considering the expressions (3) and (4) can be represented as:

$$K = \sigma_{общ}\sqrt{\pi l} = \left(\frac{4pf}{\pi} + \frac{\alpha E\Delta T}{1-\nu}\right)\sqrt{\pi l}\,. \tag{25}$$

Then, through integrating the Paris equation, we can obtain an expression for determining the number of cycles necessary for breaking:

$$N_F = \int_{l_i}^{l_c} \frac{dl}{C\left(\frac{4pf}{\pi} + \frac{\alpha E\Delta T}{1-\nu}\right)^n \sqrt{\pi l}} = \frac{2}{\pi^{1/2}(n-2)C\left(\frac{4pf}{\pi} + \frac{\alpha E\Delta T}{1-\nu}\right)^n}\left(\frac{1}{l_i^{\frac{n-2}{2}}} - \frac{1}{l_c^{\frac{n-2}{2}}}\right). \tag{26}$$

The critical crack length can be determined from the expression (25) given that the supercritical fracture point occurs at $K = K_{1c}^f$. Then

$$l_c = \frac{K_{1c}^f}{\pi\left(\frac{4pf}{\pi} + \frac{\alpha E\Delta T}{1-\nu}\right)^2}\,. \tag{27}$$

Substituting the value l_c into the equation (26), we can obtain an expression for the wear resistance criterion in the case of a combined effect on the sliding friction surface and thermomechanical stresses:

$$N_F = \frac{2}{\pi^{1/2}(n-2)C\left(\frac{4pf}{\pi}+\frac{\alpha E\Delta T}{1-\nu}\right)^n}\left(\frac{1}{l_i^{\frac{n-2}{2}}}-\frac{\pi^{\frac{n-2}{2}}\left(\frac{4pf}{\pi}+\frac{\alpha E\Delta T}{1-\nu}\right)^{n-2}}{K_{1c}^{f(n-2)}}\right). \qquad (28)$$

A combined effect on the friction surface is possible under an elastic pulsating contact with the application of thermomechanical stresses. In this case, the equation (18) should be written as:

$$N_F = \frac{2}{(n-2)C}\left(\frac{6.65}{\sigma_{z\max}+\frac{\alpha E\Delta T}{1-\nu}}\right)^n\left(\frac{1}{l_i^{\frac{n-2}{2}}}-\frac{1}{l_c^{\frac{n-2}{2}}}\right). \qquad (29)$$

Given that in this load case $l_c >> l_i$, we obtain the expression for the wear resistance criterion for elastic pulsating contact with thermomechanical fatigue

$$N_F = \frac{2\cdot 6.65^n}{(n-2)C\left(\sigma_{z\max}+\frac{\alpha E\Delta T}{1-\nu}\right)^n l_i^{\frac{n-2}{2}}}. \qquad (30)$$

Discussion and Conclusions. Analytical dependences are obtained for calculating the wear resistance index N_F for various working conditions of a stamping tool based on general criteria describing the crack resistance parameters of materials n and C. The results can be used in the design and optimization of a stamping tool operating under various loading conditions, as well as under predicting its life cycle.

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